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Original Research

The Impact of Digital Finance on Carbon Emission Performance -An Empirical Analysis of 261 Cities in China

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Abstract

To alleviate resource and environmental constraints and realize high-quality development, it is inevitable for China to reach peak carbon emissions by 2023 and carbon neutrality by 2060. This requires extensive, systematic, and profound socioeconomic reforms which are indispensable with the strong support of digital finance. The present study investigates to what extent digital finance affects carbon emission performance and the underlying mechanisms based on data about 261 cities in China from 2011 to 2021. The methods include the panel regression model, the instrumental variable method, and the mediating effect model. According to empirical results, firstly, digital finance effectively diminishes the intensity of carbon emissions, improves carbon efficiency in three dimensions, and ameliorates performance in carbon emissions. Secondly, digital finance decreases carbon emission intensity, raises carbon efficiency, and improves carbon emission performance through the innovation effect, industrial upgrading effect, and entrepreneurial effect. Thirdly, the impacts of digital finance on the performance of carbon emissions have shown remarkable discrepancies in different regions, with a better alleviation outcome in the central and eastern regions of China. Therefore, in the future, the Chinese government should vigorously boost digital finance development, continue to promote the integrated development of the real economy, financial services, and digital technologies, and keep optimizing resource allocation to facilitate peak carbon emissions and carbon neutrality.

Keywords: digital finance, carbon emission intensity, carbon efficiency, mediating effect, regional heterogeneity

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Introduction

Since the reform and opening up in 1978, China has maintained a medium-to-high economic growth rate and grown into a rapidly expanding major economy, yet the factor-driven economic growth characterized by high energy consumption has resulted in huge carbon emissions, serious environmental pollution, and damaged economic or social sustainability. As carbon dioxide (CO_2) is considered an emphatic factor causing global warming and climate change, the international community attaches great importance to carbon emissions reduction. In order to restrain greenhouse gas (e.g., carbon dioxide) emissions, the Chinese government committed to achieving the peak carbon emissions by 2030 and decreasing carbon emissions intensity by 60–65 percent compared to 2005. Then, at the 75th session of the UN General Assembly held in September 2020, Chinese President Xi Jinping clearly proposed the "dual carbon" goals of "peak carbon emissions by 2030 and carbon neutrality by 2060. Under the circumstances, the Chinese government has adopted strategies to regulate industries that generate high emissions and environmental pollution. In promoting industrial transformation with large-volume and high-intensity carbon emissions, the challenges in energy structure adjustment, technology R&D and innovation, and industrial upgrading must be tackled. All of these initiatives require substantial financial commitments. However, most companies don't have sufficient R&D funds and are subject to prominent financing constraints. Thus, it is imperative to boost the low-carbon economy during the "new normal" phase of China's economy.

Numerous researchers have conducted extensive explorations of the correlation between economic development and carbon emissions, but no consensus has been reached so far [1–4]. Many scholars have discussed the impacts of traditional finance on carbon emissions, and the viewpoints can be roughly divided into three categories [5, 6]. Firstly, traditional finance alleviates financing constraints, stimulates economic activities, and it enhances economic growth, but also increases energy consumption, generates more carbon emissions, and intensifies environmental pollution [7, 8]. Secondly, traditional finance can curb carbon emissions and improve environmental quality by supporting new energy development, uplifting technological innovation, and promoting industrial upgrades [9–11]. Thirdly, inspired by the environmental Kuznets curve, some scholars believe that the association between traditional finance and carbon emissions is nonlinear [12]. Moreover, factors (energy consumption, human capital, and technological innovation) generate non-linear impacts on carbon emissions [13–15]. Notably, digital finance explicitly improves the availability of financial resources and profoundly influences every aspect of people's lives and industrial production [16, 17]. Besides, there are divergent opinions on the relationship between digital finance and carbon emissions. Firstly, some studies hold that digital finance has played an energetic role in reducing customer acquisition costs and credit investigations, alleviating information asymmetry between the supply and demand of financial resources, and promoting the development of the green economy [18–22]. Secondly, some scholars hold that digital finance positively affects carbon emissions [23, 24]. Thirdly, the relationship between digital finance and carbon emissions is nonlinear or remains unclear [25-28].

There is no doubt that decarbonization is inseparable from efficient financial services, but market imperfections such as imperfect competition, externalities, and asymmetric information in the conventional financial system diminish financial allocation efficiency, induce resource misallocation, and weaken the financial carbon emission reduction effect. "Dual carbon" goals entail higher requirements for innovative finance. Currently, digital technologies like big data, the Internet, and cloud computing have promoted the rapid development of digital finance and contributed remarkably to the availability of financial resources. Moreover, digital finance can probably rectify "attribute mismatch", "field mismatch", and "stage mismatch" in traditional finance, providing necessary conditions for alleviating enterprises' financing constraints and improving technological innovation. On the other hand, digital finance can improve financial institutions' guidance and integration of scattered social resources, optimize capital allocation, and accelerate the flow of resources among industrial sectors. In other words, digital finance creates opportunities in industrial transformation and upgrading, technological innovation and R&D, etc., thereby facilitating faster realization of "dual carbon" goals [1]. Additionally, the development of digital finance is conducive to expanding public participation in environmental protection, significantly improving financial efficiency, and reducing transaction costs and resource consumption. In addition, digital finance provides technological reserves and product application incentives for green consumption, improving carbon emission efficiency [29–32]. However, it remains unclear whether digital finance can affect carbon emission performance, which covers two dimensions: carbon emission intensity and carbon efficiency. When carbon emission intensity is smaller and carbon efficiency is higher, the carbon emission performance will be better. This is how this influence is achieved.

China is getting closer to the time limitation for "dual carbon" goals. Meanwhile, digital finance is developing vigorously. In order to facilitate sustainable economic growth and enhance environmental protection, it is meaningful to analyze to what extent digital finance affects carbon emission performance and what mechanisms exert this ascendancy. This study explores the influences of digital finance on carbon emissions performance, the underlying mechanisms, and regional heterogeneity in 261 prefecture-level cities in China from 2011 to 2021 and recommends several feasible strategies capable of boosting digital finance development and improving carbon emission performance. So, this paper is innovative in three aspects. First, it evaluates 261 Chinese cities' performance in carbon emissions with dual indicators, namely carbon emission intensity and carbon efficiency. The data is more refined and abundant, and the evaluation indicators are more comprehensive and efficient compared with most current studies. Second,

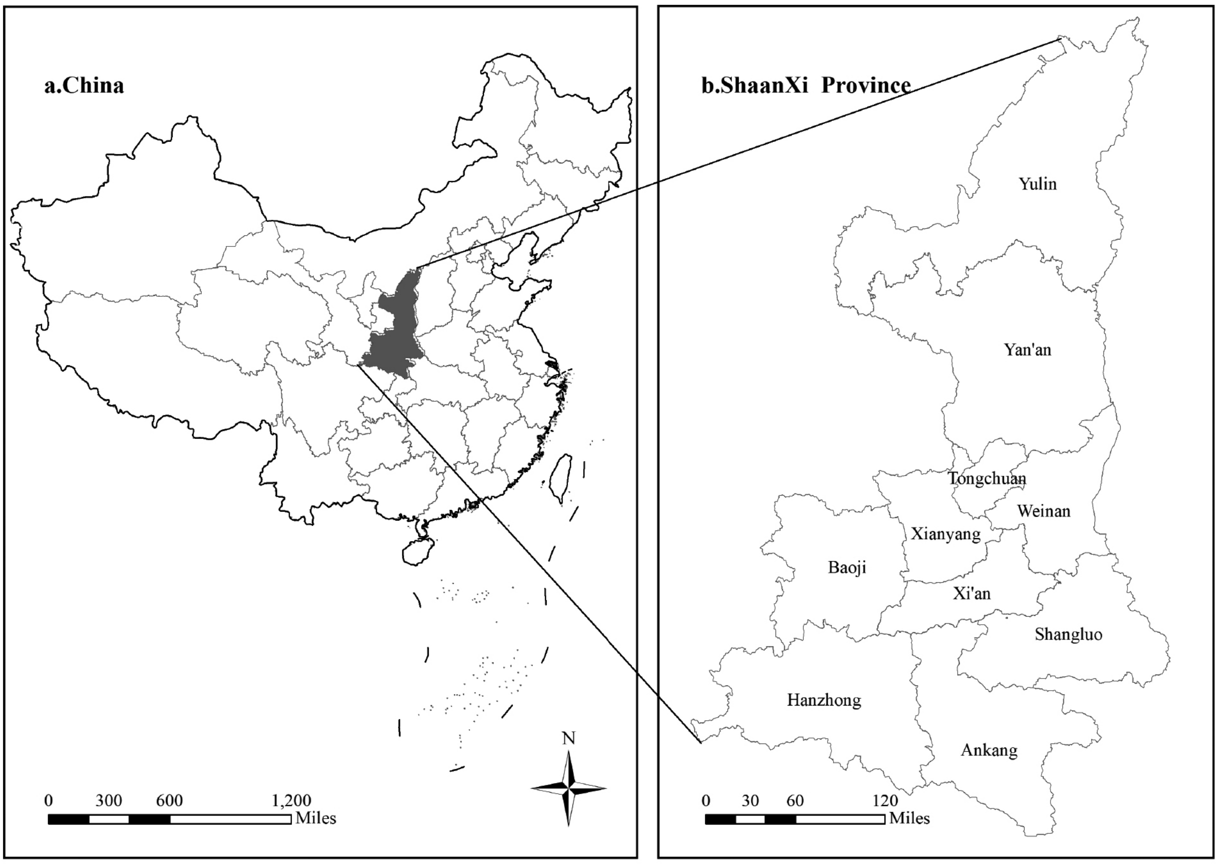

Fig. 1. Geographical location of Shaanxi Province, China.

various methods, such as the instrumental variable method, the fixed effects model, the SBM model, and the mediation effect model, are used to analyze regression coefficients, heterogeneity analysis, endogeneity, and robustness tests, which enhance the accuracy and credibility of quantitative analysis. Third, on the basis of quantitative analysis, this paper delves into the mechanism and identifies the significance of the industrial upgrading effect, innovation effect, and entrepreneurial effect caused by digital finance for improving carbon emissions performance. Thus, this study is more deep-going and targeted than most of the others. The remaining content is as follows: 2. Models and variable descriptions; 3. Results and discussion; 4. Conclusions and policy recommendations.

Methods and Variable Description

Model Setting

A fixed effects model is employed to analyze the relationship between digital finance and carbon emissions. Apparently, carbon emissions are affected by many factors. In order to improve estimation accuracy, we built the following two-way fixed effects model:

$$C_{it} = \alpha_1 Df_{it} + \alpha_2 X_{it} + \alpha + \beta_i + \lambda_t + \mu_{it} \tag{1}$$

where C_{it} represents carbon emission intensity Cai_{it} or carbon efficiency Cae_{it}, Df_{it} indicates digital finance index, x_{it} is control variables, β_i represents regional effects that do not change with time, λ_t means time effect, μ_{it} and demonstrates disturbance term with a normal distribution.

Formula (1) only deals with the general relationship between digital finance and carbon emission performance. However, what is the mechanism behind it? According to the pertinent theoretical analysis, digital finance mainly influences carbon emissions performance via the innovation effect, the industrial upgrading effect, and the entrepreneurial effect. So, we conducted empirical tests on their mediating effects and built the following models:

$$M_{it} = \alpha_1 Df_{it} + \alpha_2 X_{it} + \alpha + \beta_i + \lambda_t + \mu_{it} \tag{2}$$

$$C_{it} = \gamma_1 Df_{it} + \gamma_2 M_{it} + \gamma_3 X_{it} + \gamma + \beta_i + \lambda_t + \mu_{it} \tag{3}$$

Where M indicates mediating variables that cover the innovation effect (Inn), industrial upgrading effect (Upg), and entrepreneurial effect (Eur); γ means the constant term, and γ_1, γ_2, and γ_3 are coefficients to be estimated. The product of γ_2 and α_1 is the degree of mediating effects.

Built on the traditional radial DEA model, we include slack variables to reduce measurement errors and take into account the impacts of undesirable output on carbon efficiency, which improves identification efficiency. When calculating carbon efficiency, we assume the SBM model contains j decision-making units composed of M input factors x, n_1 expected outputs a, and n_1 unexpected outputs b.

$$\rho = \frac{1 - \frac{1}{M}\sum_{i=1}^{M}\frac{\bar{s}_i}{x_{ki}}}{1 + \frac{1}{n_1 + n_2}\left(\sum_{r=1}^{n_1}\frac{s_r^a}{a_{kr}} + \sum_{l=1}^{n_2}\frac{s_l^b}{b_{kl}}\right)}$$

$$\text{s.t.} = \begin{cases} x_{ki} = \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j + \bar{s}_i & \lambda = 1, \ldots, M \\ a_{rk} = \sum_{j=1, j\neq k}^{n} a_{rj}\lambda_j - s_r^a & r = 1, \ldots, n_1 \\ b_{lk} = \sum_{j=1, j\neq k}^{n} b_{lk}\lambda_j - s_l^b & l = 1, \ldots, n_2 \end{cases}$$

$$\lambda_j \geq 0,\ \bar{s}_i \geq 0,\ s_r^a \geq 0,\ s_l^b \geq 0,$$

In this formula, ρ refers to carbon efficiency. If $\rho = 1$, it reflects the effectiveness of the production unit. If $\rho < 1$, there is efficiency loss in the production unit, which can be made up by optimizing inputs and outputs. $\bar{s}_i$, s_r^a and s_l^b are the slack variables of inputs, ideal outputs, and non-ideal outputs, respectively. λ indicates the weight of the decision-making unit.

Variable Description

Response Variable

The response variable herein is carbon emission performance, which covers two dimensions: carbon emission intensity (Cai) and carbon efficiency (Cae). Cai is the ratio of urban carbon emissions to actual regional GDP, while Cae is obtained through the SBM-Undesirable model, which includes undesirable outputs [24]. When carbon emission intensity is smaller and carbon efficiency is higher, the performance of carbon emissions will be better. Besides, we use data on NPP-VIIRS nighttime light to inversely deduce urban carbon emissions. In recent years, there has been an extensive application of carbon emission simulated measurement based on NPP-VIIRS nighttime light in economic research. The logic behind this is that when the brightness of nighttime light is higher, it usually means the city's nighttime economy is more active, which promotes economic growth and increases energy consumption.

Explanatory Variables

The key explanatory variable herein is the digital finance index (Dfi). Its proxy variable is the digital financial inclusion index from "Digital Financial Inclusion Index" which was released by the Institute of Digital Finance at Peking University [27]. This index measures digital finance at the national, provincial, and city levels and covers three sub-dimensions, namely breadth, depth, and degree of digitalization. Breadth (Bre) covers three indicators: the number of Alipay accounts, the proportion of users linking bank cards with Alipay, and the proportion of bank cards linked with Alipay accounts, which reveal digital finance coverage. Depth (Dep) includes such services as investment, insurance, credit, and monetary funds, which reflect that more digital financial tools are available today. The degree of digitalization (Dig) covers mobility, convenience, and affordability, manifesting to what extent digital finance is integrated with digital technologies as well as inclusiveness.

Mediating Variables

The mediating variables are (1) The innovation effect (Inn), measured with per capita patents granted. (2) The industrial upgrading effect (Upg), represented by the ratio of tertiary industry added value to secondary industry added value. (3) The entrepreneurial effect (Eur), is represented by the ratio of urban individuals and private employees to employees in public institutions.

Control Variables

Based upon current studies, the variables possibly influencing carbon emission performance are identified as follows: (1) Fiscal expenditure (Gov), indicated by the ratio of fiscal expenditures to GDP. (2) Population density (Poi), indicated by a population per square kilometer. (3) Foreign direct investment (Fdi), represented by the ratio of actual use of foreign capital to GDP. (4) Financial development level (Fnd), represented by the ratio of year-end total deposits and loans of financial institutions to GDP. (5) Environmental regulation (Enr); the proxy variable is the overall utilization rate of industrial solid waste.

Results and Discussion

Benchmark Regression Results

With the above benchmark model, we estimate the relationship between digital financial development and carbon emission performance with a fixed effects model. Table 1 reflects the regression results. When taking carbon emission intensity (Cai) as an explained variable, we observe remarkably negative performance (statistically significant at 1% and 5% levels) of the digital finance index (Dfi) whether control variables are added or not. This indicates the positive role of digital finance in effectively reducing carbon emission intensity and lowering unit production of CO_2. When taking carbon efficiency (Cae) as an explained variable, we observe substantially positive performance (significant at the 1% level) regardless of whether control variables are considered or not. This suggests the positive effect of digital finance on elevating carbon efficiency.

Table 1. Benchmark regression results.

	Cai	Cai	Cae	Cae
Dfi	-0.0191***	-0.0067**	0.0036***	0.0013***
	(0.0028)	(0.0031)	(0.0004)	(0.0004)
Gov		- 0.1787		-0.1397***
		(0.4609)		(0.0509)
Poi		0.5897		-0.1571
		(0.9673)		(0.1036)
Fdi		-17.6337*		-0.2835
		(9.9711)		(1.1431)
Fnd		0.9821***		-0.1985***
		(0.1070)		(0.0134)
Enr		-0.1054		0.0095
		(0.1061)		(0.0125)
CT	3.1602***	2.0071***	0.2667***	0.5246***
	(0.1578)	(0.2296)	(0.0193)	(0.0274)
City	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes
R^2	0.1220	0.1714	0.0710	0.1 992

Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance level at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

The Analysis of Sub-Dimensions

The indexes of digital finance cover three sub-dimensions, i.e., breadth, depth, and degree of digitalization. In order to further examine which sub-dimension affects carbon emission performance, we perform estimation with a two-way fixed-effect model. Table 2 reflects the regression results, and the breadth of digital finance coverage significantly alleviates carbon emission intensity, while all three sub-dimensions sensibly increase carbon efficiency.

Increases in digital financial breadth (Bre) suggest that financial services can overcome previous constraints and become available to small, medium, and micro enterprises by integrating traditional finance with contemporary digital technologies. The higher output value of financial services promotes regional industrial structure upgrading and contributes to better performance in terms of carbon emissions. Regarding the depth of digital finance (Dep), increased depth demonstrates higher availability of financial products with more investment, credit, monetary funds, insurance, and other businesses. Abundant financial tools are effective in motivating enterprises' investment in R&D and improving resource utilization efficiency, thus ameliorating performance terms of carbon emissions. The higher degree of digitization (Dig) indicates enhanced integration of finance and digital technologies. So, financial institutions assist enterprises in data capture, analysis, and decision-making with the help of digital technology like cloud computing and big data, thereby offering credit support for companies with potential R&D capabilities. Furthermore, companies can increase carbon efficiency and carbon emission performance through technological innovation. Digital finance effectively encourages companies to acquire loans directly from online platforms, which boosts financial circulation, avoids enterprises' carbon emissions caused by visiting financial institutions offline, and reduces resource waste, thereby improving urban carbon emission performance.

Endogeneity Testing

Specifically, we lag the explanatory variable by one period; columns (1) and (2) of Table 3 reflect the results. They show that the impact of Dfi (L.Dfi), lagged by one period, on carbon emission intensity is markedly negative, while its effect on carbon efficiency is positive, aligning with the baseline regression results. This reveals the positive role of digital finance in improving carbon emission performance in sustainable ways. On the other hand, we develop an instrumental variable by constructing an exogenous variable highly related to digital finance but not relevant to error terms and conduct regression using two-stage least squares (2SLS). The internet penetration rate (Inp) is taken as an instrumental variable in digital finance. Columns (3)

Table 2. Analysis of digital finance sub-dimensions.

	Breadth		Depth		Degree of digitalizatio	
	Cai	Cae	Cai	Cae	Cai	Cae
Bre	-0.0088***	0.0008**	*			
	(0.0028)	(0.0004)				
Dep			0.0031	0.0014***		
			(0.0022)	(0.0002)		
Dig					-0.0015	0.0003***
					(0.0009)	(0.0001)
CT	2.1333***	0.6509***	1.4141***	0.5120***	1.6889***	0.5838***
	(0.2151)	(0.0274)	(0.1924)	(0.0218)	(0.1442)	(0.0164)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.1565	0.1497	0.1143	0.2165	0.1444	0.1802

Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance level at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

Table 3. Regression results of endogeneity testing.

	Lagged explanatory variabl		Instrumental variable	
	Cai	Cae	Cai	Cae
L.Dfi	-0.0131***	0.0018***		
	(0.0036)	(0.0004)		
Inp			-0.0032***	0.0007*
			(0.0007)	(0.0003)
CT	2.1614***	0.4905***	1.9248***	0.7458***
	(0.2551)	(0.0287)	(0.1217)	(0.0445)
CVs	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes
R^2	0.1763	0.2105	0.1590	0.0889
Cragg-Donald Wald F			200.08	233.78

Note: Numbers in parentheses indicate the standard deviations of estimated coefficients. ***, **, and * are significance level at 1%, 5%, and 10%. R^2 refers to overall R^2.

and (4) of Table 3 manifest regression results. The Cragg-Donald Wald F test rejects the null hypothesis of a weak association between endogenous variables and instrumental variables, which suggests that the instrumental variables selected are reasonable. In summary, empirical results are still reliable when endogeneity is taken into account.

Robustness Testing

Referring to current research, we implement a robustness test by changing explanatory variables and explained variables and selecting sub-samples (the results are shown in Table 4). The results of replacing explanatory variables are shown in columns (1) and (2). Considering the close relationship between digital finance and the economy, we operate the comprehensive development index of the digital economy (Dfr) to replace digital finance (Dfi). Based on data availability, we have chosen four indicators: Internet penetration rate, which represents the number of broadband Internet users per 100 individuals; profile of practitioners, which represents the proportion of people working in software and computer services; output, which represents the total

Table 4. Regression results of robustness testing.

	Replace explanatory variables		Replace explained variables		Sub-sample
	Cai	Cae	Cas	Cai	Cae
Dfi			-0.0032***	-0.0089***	0.0019***
			(0.0010)	(0.0005)	(0.0006)
Dfr	-0.4663***	0.1224**			
	(0.0685)	(0.0512)			
CT	1.8070***	0.6044***	2.0261***	2.8023**	0.1309***
	(0.1415)	(0.0299)	(0.0739)	(1.3364)	(0.3516)
Cvs	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes
R^2	0.1276	0.1835	0.1350	0.1914	0.2416

Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance level at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

quantity of telecommunications services available per person; and mobile phone penetration rate, which represents the number of cellphone users per 100 individuals. The original data comes from the China City Statistical Yearbook. Through principal component analysis, we standardize data about the four indicators and then nondimensionalize them to get the comprehensive development indicator of the digital economy. It can be seen that the explanatory variable Dfr obviously improves carbon emission performance. Column (3) represents the regression result of replacing the explained variables. Besides, we replace per capita carbon emissions (Cas) with carbon emission intensity (Cai). The regression coefficient of Dfi on Cas displays a significantly negative performance at 1%, implying the positive role of digital finance in effectively dwindling per capita carbon emissions. In addition, considering the influence of sample size on empirical results, we further examine the relationship between digital finance and carbon efficiency and intensity using sub-sample data from 2016 to 2021. Columns (4) and (5) proclaim a positive effect of digital finance on abating carbon emission intensity and enhancing carbon efficiency, which further ensures the reliability of regression results.

Analysis of the Mediating Effect

This part covers further exploration of the mechanism that promotes digital finance to improve carbon emission performance. Table 5 and Table 6 show the mediating effect model from carbon emission intensity and carbon efficiency aspects, as shown in columns (2) and (3).

We measure the urban innovation effect (Inn) with per capita patents, and columns (1) and (2) of Tables 5 and 6 show regression results, respectively. The innovation effect serves as a mediator that adjusts the impact of digital finance on environmental pollution, increases the effectiveness of finance supply, and directly promotes technological innovation activities, thereby reducing carbon emissions and raising carbon efficiency simultaneously, thus improving carbon emission performance. The industrial upgrading effect (Upg) is represented by the ratio of tertiary industry added value to secondary sector added value, with columns (3) and (4) of Tables 5 and 6 manifesting the regression results. Moreover, financial development is essential for impelling industrial transformation and structure upgrading, so as to facilitate pollution reduction and improve carbon emission performance. We employ the ratio of urban individual and private employees to employees in units to represent the entrepreneurial effect (Eur), with columns (5) and (6) of Tables 5 and 6 indicating the regression results. The entrepreneurial effect has passed the test at a significance level of 5%. Fully exerting its strengths of "fast speed, low cost, and wide coverage" and perfectly combining the advantages of digital technologies in scenarios, data, information, etc., digital finance overcomes the defects of conventional financial services and effectively solves the financing constraints of farmers, micro, small, or medium-sized companies, and other vulnerable groups.

Heterogeneity Analysis

Compared with traditional financial services, digital finance can provide financial services for disadvantaged groups in backward or remote areas, and alleviate financial exclusion or repression. To clarify the relationship between digital finance and carbon emission performance in different regions, a heterogeneity analysis is required. According to the economic region division standard of the National Bureau of Statistics of China, the total samples are categorized into western, eastern, and central regions, and Table 7 manifests the regression results.

Table 5. Mechanism regression: from the perspective of carbon emission intensity.

	Innovation effect		Industrial upgrading effect		Entrepreneurial effect	
	Inn	Cai	Upg	Cai	Eur	Cai
Dfi	0.0541**	-0.0068**	0.0054**	-0.0112***	0.0047**	-0.0129***
	(0.0239)	(0.0031)	(0.0023)	(0.0037)	(0.0024)	(0.0039)
Inn		-0.0022				
		(0.0025)				
Upg				-0.0468		
				(0.0358)		
Eur						-0.2897**
CT	2.5797	2.0129***	0.5971***	2.0779***	0.6914***	2.2923***
	(1.7699)	(0.2297)	(0.1724)	(0.2807)	(0.1773)	(0.2973)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.0464	0.1693	0.1067	0.2140	0.2080	0.2065

Sobel (p-value) Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * are significance level at 1%, 5%, and 10%. R^2 indicates the overall R^2.

Table 6. Mechanism regression: from the perspective of carbon efficiency.

	Innovation effect		Industrial upgrading effect		Entrepreneurial effect	
	Inn	Cae	Upg	Cae	Eur	Cae
Dfi	0.0541**	0.0013***	0.0054**	0.0013***	0.004**	0.0012**
	(0.0239)	(0.0004)	(0.0023)	(0.0004)	(0.0024)	(0.0005)
Inn		0.0004				
		(0.0003)				
Upg				0.0013		
				(0.0041)		
Eur						0.0017
						(0.0046)
CT	2.5797	0.5229***	0.5971***	0.4917***	0.6914***	0.4992***
	(1.7699)	(0.0274)	(0.1724)	(0.0333)	(0.1773)	(0.0362)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.0464	0.1940	0.1067	0.1446	0.2682	0.2416

Sobel (p-value) Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance level at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

Perspective of Digital Finance

As for carbon emission intensity (Cai), the coefficients of digital finance (Dfi) in Table 7 are all negative and statistically significant in central and eastern regions, but not significant in the western region, indicating that digital finance development in different regions dilutes carbon emission intensity, but the magnitude of the emission reduction effect varies. In the eastern region, digital finance not only causes substantial cost reduction but also expands financial services accessibility with great inclusiveness, provides efficient financial services for vulnerable groups, and promotes economic development. In terms of carbon efficiency (Cae), as shown in Table 7, regression in different

Table 7. Heterogeneity of the impacts of digital finance on carbon emission performance.

	Eastern China		Central China		Western China	
	Cai	Cae	Cai	Cae	Cai	Cae
Dfi	-0.0111***	0.0023***	-0.0193***	0.0010*	-0.0081	0.0012
	(0.0038)	(0.0006)	(0.0064)	(0.0006)	(0.0072)	(0.0009)
CT	2.5775***	0.3799***	2.3719***	0.7258***	2.0685***	-0.3054**
	(0.3088)	(0.0524)	(0.5492)	(0.0513)	(0.5672)	(0.1260)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.3694	0.2380	0.2565	0.3883	0.0219	0.0247

Note: Numbers in parentheses refer to the standard deviations of estimated coefficients. ***, **, and * indicate significance level at 1%, 5%, and 10%. R^2 is overall R^2.

Table 8. The impacts of digital finance breadth on carbon emission performance.

	Eastern China		Central China		Western China	
	Cai	Cae	Cai	Cae	Cai	Cae
Bre	-0.0095***	-0.0010*	-0.0245***	-0.0023***	0.0064	0.0008
	(0.0032)	(0.0006)	(0.0056)	(0.0006)	(0.0059)	(0.0009)
CT	2.4666***	0.6133***	2.6103***	0.7943***	2.1534***	0.8147***
	(0.2760)	(0.0477)	(0.5152)	(0.1264)	(0.5532)	(0.0657)
Cvs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.3603	0.1564	0.1684	0.3778	0.0245	0.0228

Note: Numbers in parentheses indicate the standard deviations of estimated coefficients. ***, **, and * refer to significance levesl at 1%, 5%, and 10%. R^2 represents the overall R^2.

regions suggests the positive function of digital finance in improving carbon efficiency, especially in the eastern region. Cities in Eastern China have sound financial resource conditions and industrial foundations. The application of digital technology greatly elevates factor allocation efficiency and energy utilization rates and increases carbon efficiency. This indicates that digital finance development will stimulate technological innovation, thereby improving carbon emission efficiency.

Perspective of Different Sub-Dimensions

Tables 8, 9, and 10 display the impacts of the breadth, depth, and degree of digitization of digital finance on carbon emissions performance in different regions. While significantly reducing carbon emission intensity in the eastern and central regions, the breadth of digital finance does not increase carbon efficiency in these areas. In contrast, the depth of digital finance contributes to higher carbon efficiency in the eastern, central, and western regions, but it only considerably reduces carbon emission intensity in the western region. The degree of digitalization shows a noticeable effect on carbon efficiency in western and eastern regions and lowers carbon emission intensity in the eastern region, but it cannot dramatically improve carbon emissions performance in the central region.

Heterogeneity analysis suggests that digital finance has a significantly dissimilar influence on carbon emissions performance in different regions. This indicates that regional heterogeneity cannot be ignored in analyzing the relationship between digital finance and carbon emissions. In particular, digital finance in backward areas should be vigorously supported. Although digital finance

Table 9. The impacts of digital finance depth on carbon emission performance.

	Eastern China		Central China		Western China	
	Cai	Cae	Cai	Cae	Cai	Cae
Dep	-0.0011	0.0021***	-0.0007	0.0009**	-0.0103**	0.0009*
	(0.0026)	(0.0004)	(0.0046)	(0.0004)	(0.0049)	(0.0005)
CT	1.7065***	0.3819***	1.3709***	0.6126***	0.0258***	0.8099***
	(0.2397)	(0.0394)	(0.5076)	(0.0452)	(0.0035)	(0.0538)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.1465	0.2133	0.3003	0.3881	0.0099	0.0333

Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance levels at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

Table 10. The impacts of the digitalization degree on carbon emission performance.

	Eastern China		Central China		Western China	
	Cai	Cae	Cai	Cae	Cai	Cae
Dig	-0.0257***	0.0007***	-0.0009	-0.0001	-0.0012	0.0371*
	(0.0037)	(0.0002)	(0.0019)	(0.0002)	(0.0017)	(0.0223)
CT	1.9702***	0.4940***	1.3739***	0.6758***	2.5152***	0.8492***
	(0.1690)	(0.0279)	(0.4402)	(0.0391)	(0.4686)	(0.0496)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.2587	0.1550	0.2976	0.3846	0.0227	0.0299

Note: Numbers in parentheses represent the standard deviations of estimated coefficients. ***, **, and * sand for the significance level at 1%, 5%, and 10%, respectively. R^2 refers to overall R^2.

has gained rapid development in China, it also witnesses large disparities in the whole country. So, we should not overlook some backward and poor regions. This requires local governments to strengthen digital finance, generalize financial expertise, and provide financial hardware in order to increase awareness and inclusive attitudes in poverty-stricken areas.

Conclusions and Policy Recommendations

Conclusions

Based on panel data from 261 cities in China from 2011 to 2021, the authors explore the relationship between digital finance and carbon emission performance using multiple methods. In this analysis, carbon emissions performance is represented by carbon emission intensity and carbon emission efficiency, and the study draws the following momentous conclusions:

First, digital finance is significant in diminishing carbon emission intensity and uplifting carbon efficiency by navigating financial resources flowing to green and low-carbon companies, thus improving performance in carbon emissions. Second, regression results from the breadth, depth, and degree of digitalization of digital finance demonstrate that digital finance could upgrade performance in carbon emissions from all three dimensions. This reveals that the integration between digital technology and finance is noteworthy in breaking down geographical constraints on traditional financial services and increasing financial circulation efficiency, thereby improving carbon emissions performance. Third, the analysis of mediating effects reveals that digital finance sweetens carbon emission performance through innovation effects, industrial upgrading effects, and entrepreneurial effects. This means digital transformation in financial services can stimulate economic growth potential, incline financial resources toward corporate R&D activities, and promote industrial structure optimization by navigating financial resources flow to clean and low-carbon industries, thus ameliorating performance in carbon emissions. Fourth, heterogeneity analysis suggests that the impact of digital finance on carbon emissions performance presents remarkable regional differences. Specifically, digital finance indubitably enhances carbon emission performance in the central and eastern regions of China, but is not distinctly influential in the western region.

The contributions of this paper are reflected in three aspects. First, refined and abundant urban data and more comprehensive evaluation indicators are utilized. Second, various methods are used to enhance the accuracy and credibility of quantitative analysis. Third, this paper delves into the mechanisms of the industrial upgrading effect, innovation effect, and entrepreneurial effect induced by digital finance for improving carbon emissions performance. However, due to the availability of data, we are unable to track the impact of digital finance development on carbon emissions in rural areas. In addition, the influence of digital finance development on carbon emissions in microhousehold sectors is also worth investigating for further research.

Policy Recommendations

This study investigates how digital finance affects carbon emission performance and provides an empirical basis and policy inspiration for reducing carbon emissions with digital finance. The policy recommendations are presented below.

First, since digital finance can effectively improve performance in terms of carbon emissions, it is suggested that the government vigorously promote digital infrastructure, boost the combination of financial services and digital technologies, and provide diversified financial product portfolios for green transformation. Moreover, the advantages of environment-friendly digital finance should be exerted to improve the allocation of financial resources through digital technologies and restrict the negative externalities of carbon emissions with market-oriented environmental tools. Second, the government should optimize capital allocation with the help of digital platforms, navigate financial resources flowing to environment-friendly innovative energy companies, provide financial support for energy technologies, and provide beneficial external conditions for green innovation. Third, cities in western China should undertake industries transferred from eastern and central China, empower traditional resources with data, raise resource utilization efficiency, and stimulate economic growth potential to boost sustainable development. Cities in eastern and central China should continue to promote green innovation and industrial structure optimization, fully utilize innovation effects, industrial upgrading effects, and entrepreneurial effects, and improve performance in carbon emissions so as to advance dual carbon goals.

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Conflict of Interest

The authors declare no conflict of interest.

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